

J. Audsley Dissertation Final

by James Audsley

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NOVEL CONCEPT FOR AN AUTOMATED AEROSPACE WIRE COIL- BUNDLE TYING SYSTEM

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**SPECTRUM
TECHNOLOGIES**

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Declaration of Authenticity:

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has lead to the award of a degree.

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Contents

<u>Description</u>	<u>Page Number</u>
Cover Page	1
Declaration of Authenticity	2
Contents Page	3
Abstract	4
Chapter 1: Project Outline & Objectives	5
Chapter 2: Timescale	6
Chapter 3: Research & Technical Resources	7
Coil Dynamics & Robot Tooling	8
Pegasus Hub	9
Coil Length & Initial Requirements	10
Felins Coil Tyer Overview	11
Schleuniger Coil Tyer Overview	12
Cyklop Coil Tyer Overview	13
Plasties Coil Tyer Overview	14
Coil Tyer Selection & Speculative Requirements	15
Chapter 4: Concepts – Coil Stacking – Concept 1	16
Concept 2	17
Concept 3	18
Concept 4	19
Concept 5	20
Concept 6	21
Concept 6 – Stacking Platen	22
Concept 6 – Coil Guides & Clamps	23
Concept 6 – Clamping Mechanism & Sequencing	24
Concept 6 – Radial Clamping Mechanism	25
Concept 6 – Radial & Axial Clamping Mechanism	26
Chapter 5: Final Concept	27
Final Concept – Handover Tooling	28
Final Concept – Handover Tooling Sequence	29
Final Concept – Handover Tooling Axis of Rotation & Torque	30
Final Concept – Handover Tooling Rotary Actuator	31
Final Concept – Handover Tooling Secondary Axis of Rotation	32
Final Concept – Handover Tooling Discussion	33
Final Concept – Handover Tooling Pivot Point	34
Final Concept – Framework and Tying Machine Mounting	35
Final Concept – Stacking Platen Finalisation	36
Final Concept – Guarding and Maintenance Access	37
Final Concept – Bundle Retrieval	38
Chapter 6: Theoretical Functional Analysis	39
Chapter 7: Conclusions and Recommendations for Further Development	40
Further Conclusions and Recommendations for Further Development	41
References & Resources	41

Abstract

The aerospace industry is continuously in demand of methods to automate its processes, to increase throughput and eliminate human error. Spectrum Technologies is actively researching opportunities to offer Turnkey solutions in this regard. During late 2017 and early 2018, Spectrum Technologies took on a government grant, to subsidise innovation within UK companies.

The British government is providing grants to British companies through the Innovate UK programme, a state funded organisation centred on enabling the development of innovative ideas. Spectrum Technologies is utilising this grant to develop an automated wire handling system.

There are numerous challenges presented in this undertaking, a few of which are noted below;

- Maximising throughput per shift
- Reducing waste wire (offcuts)
- Reducing labour downstream
- Minimising cycle time through efficient movement

One such solution is to engineer a way to bundle coils of wire together within a robot handling cell, enabling ease of sorting, minimising errors and ensuring efficiency. This bundling occurs downstream from a high-speed laser wire marker and coiling system. The bundles are then collected together automatically, and, using a tying system, held together. The bundle is then transported to a collection carousel, to allow removal from the system by hand.

The justification for such an undertaking is the result of feedback and experience from various wire production workshops within larger companies. Most wire errors only become obvious during the installation stage, for example, if wire lengths are too long/short, or are the wrong wire type altogether. This carries heavy penalties regarding aircraft production schedules. The most probable root causes of such errors are likely a combination of human error and equipment inadequacies.

This report aims to detail and comprehensively break-down a concept for automated aerospace wire coil handling and tying, to mitigate the risk of human error and downstream system shortfalls within a production line.

Such a system takes the form of the Spectrum Technologies Pegasus Plus, or Pegasus+ Automated Wire Handling System.

The system comprises of the laser wire marker, coiling system, wire stripper, bundle tying system and coil collection unit. A robot with a dedicated end effector assembly is positioned centrally between the modules.

The bundle tying system will reduce downstream handling and sorting requirements for manufacturing facilities, thereby increasing productivity and throughput while reducing errors and costly rectification work due to wires being grouped incorrectly, while the coiling system is a means of automatically checking the physical length of a given wire against the programmed value. Short wire lengths can be catastrophic to a business, as they are mostly not recognised until installation, which is the latest and most costly stage at which to rectify the error.

Chapter 1: Project Outline & Objectives

Spectrum Technologies has been approved to receive funding for new business development via the Innovate UK grant scheme (see link below)

<https://www.gov.uk/government/organisations/innovate-uk>

Spectrum Technologies are utilising this grant to develop an automated wire processing system, which uniquely applies, but is not limited to, the following technologies/techniques;

- Wire/cable de-reeling
- Laser wire/cable marking
- Wire/cable coiling with optional ID label
- Wire/cable linear and rotary laser stripping
- Wire/cable crimping
- Wire/cable slug removal (partial and full)
- Wire/cable coil stacking and tying
- Wire/cable coil collection and presentation

The WP (Work Package) undertaken encompasses the mechanical design of the wire/cable coil stacking and tying module. Designated as WP3135, this module will facilitate handover of an untied, formed coil of wire/cable from a robot end effector, stack various or alike coils on a platen, and present these coils to a tying machine. At the end of the tying cycle, the robot will use a hooked implement to pick up the 'bundle' and place it onto a specified peg within the collection unit.

This module will serve to test various aspects with regard to throughput and automation, as such it has a so-called 'open specification', whereby the specifics and requirements for the system are subject to change and are not finite as they would be within a full product design specification. Some elements are required however, such as the tying machine and stacking assembly are to be entirely pneumatic, using reed switches as sensors to govern positioning and timing. These sensors connect to local IO (Input/Output) blocks that feed back to the PLC (Programmable Logic Controller) within the coiling machine.

The overall aim of the module is to provide a completely automated means of bundling select wires/cables together in a repeatable manner, eliminating human error when creating grouping wires together. In the aerospace industry, manufacturing plants span multiple square miles (Boeing, 2018), and such errors can cause costly delays, if technicians do not have the correct wires/cables.

If the wire is too short, it must be removed and replaced, costing time and money to rectify. If a wire is too long, it must be cut down within the aircraft. This is undesirable as it directly introduces FOD (Foreign Object Debris) into the aircraft, in the form of small offcuts of wire/strands of insulation. These can lead to electrical shorts, or more severely, if they were to fall inside an engine or other critical mechanism, the safety of that system would be compromised. Therefore, long wires are also undesirable, and must be removed and replaced. It could be argued that it is simply quicker to install longer wires without cutting down, to save the costly and time-consuming replacement work. Leaving these wires in place would carry a weight penalty. This would adversely affect the efficiency of the aircraft over its life, especially if multiple lengths of wire are too long. Longer wires also disrupt the compactness and form of wire harnesses within an aircraft, this can make them difficult and even impossible to fit, especially when harnesses are required to be passed through narrow bulkheads or around components, etc.

Chapter 2: Timescale

The allocated time planned for this WP spans from the 13th April to the 15th June 2018. Units of time are in days, and are rough estimates agreed upon by the mechanical engineering team within Spectrum Technologies.

A snapshot of the Microsoft Project Plan is shown below;



Figure 1 - Innovate UK Project Plan Snapshot – Spectrum Technologies - 2018

The above plan is for the benefit of progress audits conducted by the Innovate UK inspection officer. In actuality, the work packages are drawn out over a longer period, as no single resource is 100% allocated to the Innovate UK project. Spectrum Technologies has several major projects underway, and they all require the attention of the engineering team. This is the result of personnel and resource changes within Spectrum Technologies and cannot be avoided.

At the time of writing, the module that this dissertation is based upon, is not yet built due to other ongoing commitments.

Chapter 3: Research & Technical Resources

This module is being undertaken with several requirements and considerations; these are as follows;

- Coil handover between the robot end effector and the bundle tying system needs to be positive, ie: at no point in time will a coil be un-clamped/un-constrained
- As per the first bullet point, stacked coils always need to be clamped axially with radial guidance, with secondary means of clamping to properly constrain a new deposited coil
- Coils will be unlabelled (normal Pegasus operation applies an adhesive identification label to the apex of a coil) – hence the first two bullet points
- Radial guidance best represented as an annulus, and maintain the structure as such wherever possible
- Coil tail end orientation must be kept constant
- Sensing of tying machine tooling position
- Module must be <1 metre in width relative to the Pegasus+ robot cell

All design work and final assembly will take place on-site at Spectrum Technologies, with part manufacturing outsourced to the relevant suppliers via an existing purchasing system. All purchase requisitions are required to have copies kept within the designated project folder, for the purpose of traceability.

The main software packages and technical documentation resources used for this project are listed below;

- Microsoft Windows 7 64 bit operating system
- Autodesk Inventor Professional 2014 – 3D Computer Aided Design software
- Autodesk Vault Basic 2014 – File management and server-side storage software
- Festo Fluid Draw – Pneumatic circuit design software
- Microsoft Project 2016 – Project planning software
- Maytec Part Community website – CAD resource for aluminium extrusion
- Festo Website – CAD resource for pneumatic components and manifold configuration
- Misumi website – Mechanical design resource for configurable components

All relevant information from component datasheets will be identified and cross checked to meet the requirements of their function. For example, where a pneumatic cylinder is required to lift an assembly, the weight of the assembly must be accounted for, to ensure that the theoretical maximum force of the cylinder is a percentage above that required.

Additional considerations include the centre of gravity of the assembly, to ensure that the maximum permissible moments in a given direction are not exceeded.

A critical consideration for this module is the behavioural tendencies and characteristics of un-labelled formed coils of wire, which are transported from the coiler to the bundler via a robotic arm, equipped with a pre-existing bespoke end effector arrangement, as below;

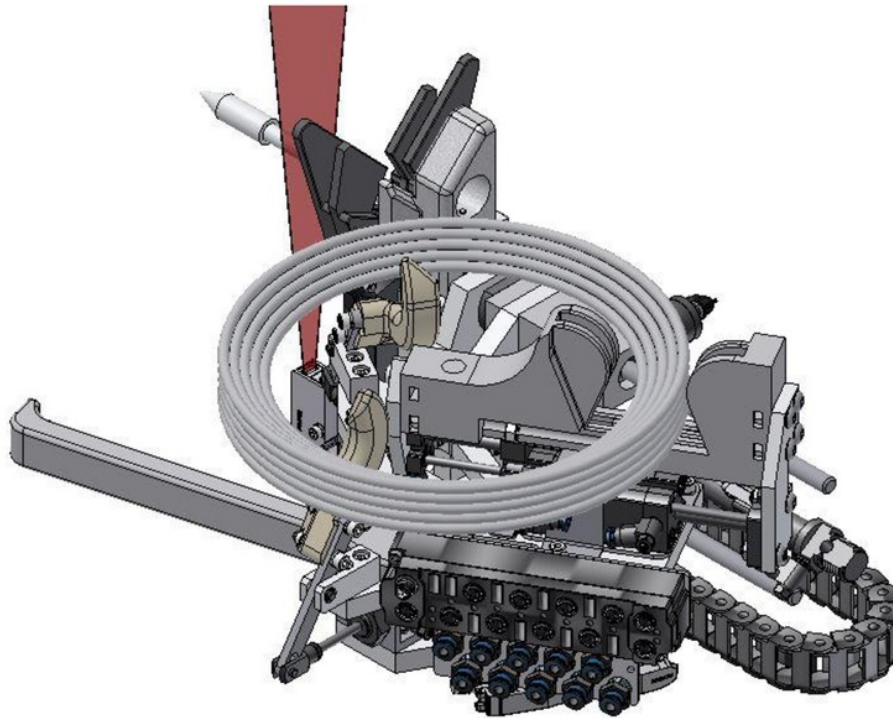


Figure 2 - Robot End Effector Tooling – Spectrum Technologies - 2018

The theoretical maximum cross-sectional area of a formed coil is 379 square mm (see Figure 3). The shape of this coil is determined by the profile of the Pegasus coiling system hub arms, which feature a 60 degree 'vee'. (see Figure 4)

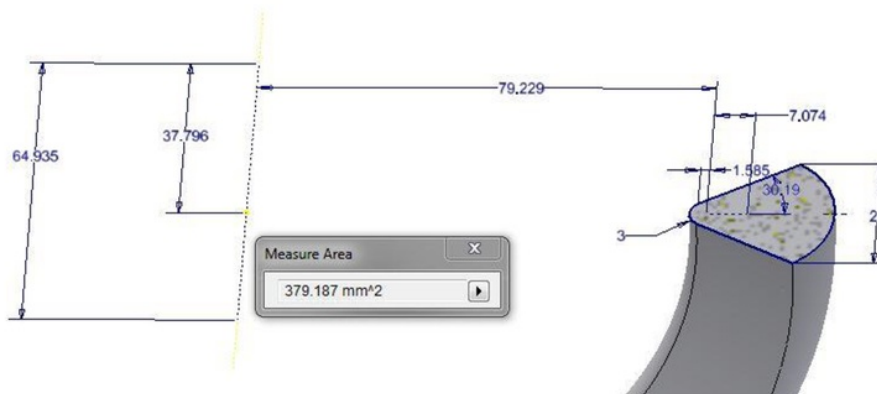


Figure 3 - Formed Coil Cross-Section – Spectrum Technologies - 2018

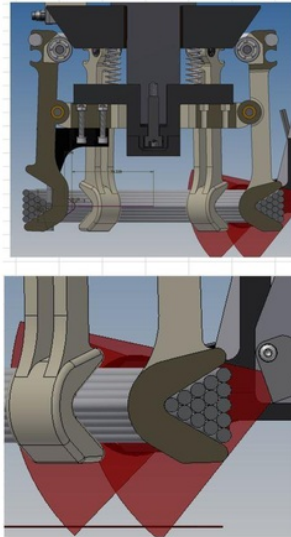


Figure 4 - Pegasus hub, coil cross-section - Spectrum Technologies - 2018

Due to the lack of a product design specification for this module, i.e.: It was intended to be a research and development module, and as such the scope would evolve in parallel with the CAD design, it was decided via informal meeting of the mechanical engineers to limit the maximum cross-sectional area of a bundle to be equivalent to 5 full size formed coils, or 1895mm^2 . (379×5). A bundle can also consist of any number of coils, provided that the sum of their cross-sectional areas does not exceed 1895mm^2 .

The behavioural tendencies of the coils are influenced by several factors, including insulation material, outside diameter, inherent memory, stiffness and insulation deformability. As such, accounting for these factors is not an exact science, therefore approximative deduction is required to provide a best-guess at how a coil will behave. Below, a snapshot of the coiling hub, which dictates the internal diameter of the coil.

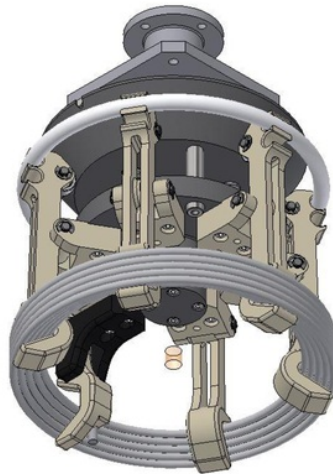


Figure 5 – Pegasus Coiling Hub - Spectrum Technologies - 2018

Coil length is variable, as is the wire/cable diameter. The below graph (Spectrum Technologies, 2018) illustrates the approximate relationship between coil length and wire diameter, for a full-size coil.

As depicted, the graph curve approximates an inverse square relationship between wire length and the outside diameter, where the maximum length decreases rapidly as the diameter increases.

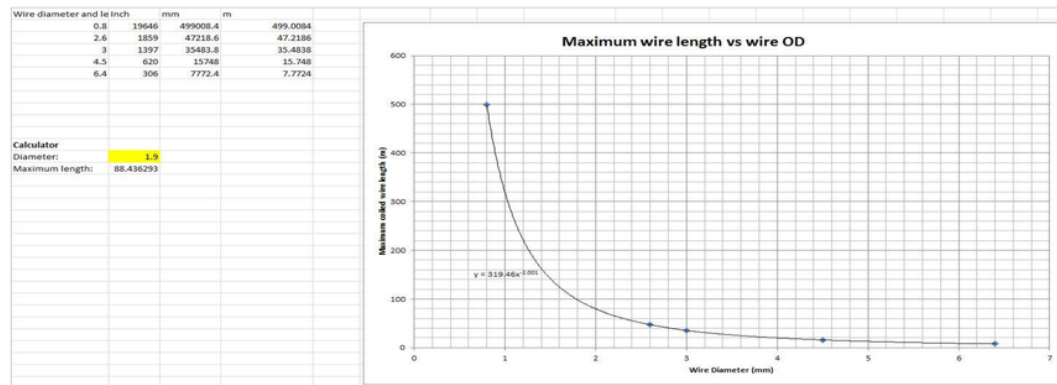


Figure 6 - Wire Length vs Wire OD Graph - Spectrum Technologies - 2018

Approximating un-labelled coil behaviour when stacked upon each other is simply unfeasible, given the number of variables at play, therefore the bundler must perform its function in such a manner that eliminates as many variables as possible. Various concepts were generated to discern the best way to approach this problem.

The first step in the development of this module is to identify a suitable means of applying ties to bundles, either through a bespoke mechanism or, more preferably, through an off the shelf system.

Requirements were identified as;

- Capability of bundling multiple wire coils
- Pneumatic operation preferable
- Maximum area of approximately 2000mm²
- Minimum area of approximately 2mm²
- Tie removal by hand preferable

The first unit is the Felins coil tyer;



Figure 7 - Felins Coil Tyer - Felins - 2018

Identified characteristics and observations;

- Ties using elastic rope
- 20 operations per minute (3 second cycle time)
- 648mm W x 1537mm H x 791mm D
- Potentially difficult motion for the robot due to the required reach to push the coil through the machine
- Potentially will require more complex robot tooling to hold the bundle in a more organised environment
- Difficult to remove tie without tools
- Material spool size is small, positioning is not optimal.
- Minimum tie size of 76mm diameter, maximum size 584mm diameter

Unit 2, Schleuniger TM66 Tying Machine;



Figure 8 - Schleuniger TM66 - Schleuniger - 2016

Identified characteristics and observations;

- Ties using elastic rope
- 100 operations per minute (0.6 second cycle time)
- 450mm W x 1230mm H x 480mm D
- Material spool size and position will incur stoppage penalties during replenishment
- Potentially difficult motion for the robot due to the required reach to push the coil through the machine
- Potentially will require more complex robot tooling to hold the bundle in a more organised environment
- Removable stand
- Difficult to remove tie without tools
- Minimum tie size of 5mm diameter, maximum size 150mm diameter
- Schleuniger known to work closely with Spectrum Technologies competitors

Unit 3, Cyklop AXRO-MD 60 XL



Figure 9 - Cyklop AXRO-MD 60 XL Tying Machine – Cyklop - 2019

Identified characteristics and observations;

- Ties using elastic rope
- 58 operations per minute (0.98 second cycle time)
- 402mm W x 925mm H x 820mm D
- Potentially difficult motion for the robot due to the required reach to push the coil through the machine
- Small material spool, and proximity to process area will incur stoppages due to replenishment
- Potentially will require more complex robot tooling to hold the bundle in a more organised environment
- Difficult to remove tie without tools
- Maximum tie size 300mm diameter

Unit 4, Plasties XL-8 Air Ring Tyer machine



Identified characteristics and observations;

- Ties using metal core twist tie material
- 40 operations per minute (1.5 second cycle time)
- 260mm W x 609.6mm H x 482mm D (cabinet)
- Open design would permit robot to position itself easily
- Open design would permit additional tooling as required
- Can remove tie without tools
- Pneumatically operated
- Removable stand
- Spool material placement and capacity is optimal
- Minimum tie size 25mm diameter, Maximum size 203mm diameter

Based on the options available for off-the-shelf tying machines, the Plasties XL-8 is the logical choice. It offers a much more open volume of space around the process area than the alternatives, allowing for greater flexibility in terms of interaction with the robot tooling. It is also entirely pneumatic, therefore there are no complex control systems to communicate with via software. Triggering the tying sequence can be achieved by vacuum switch or by connecting the relevant valve within the machine to an external PLC (programmable logic controller) controlled valve manifold (also required for additional tooling to aid coil stacking/bundling and coil control)

The Plasties machine can also be orientated at any angle, which is significantly beneficial when presenting a bundle to the machine, as gravity will interfere with efforts to control and constrain the coils.

As the tying machine is now specified, concepts for a mechanism to interact with it must be generated, taking into account the requirements mentioned on page 6 of this document.

The design challenge now faced is in regard to the bundling of the coils from the robot tooling. The coils must be neatly stacked on some form of platen and constrained so as to minimise deformation of the coils. This platen must also be able to position itself, and the coils, in such a way as to allow the tying machine to perform a successful tie.

Any apparatus to constrain the stacked coils must not obstruct the robot tooling when placing a new coil, and must not obstruct the tying machine operation. Another challenge here is that the robot tooling (shown in figure 2) was never intended to perform handover operations whereby a coil is transferred under control to another mechanism. As such, the design of the robot tooling will not lend itself to a simple means of coil control on the platen.

Also, given that the tying machine is entirely pneumatic, it is therefore desirable to maintain this throughout the module. The valves will be electronically controlled via IO (input output) blocks that feed into an external PLC unit embedded in the Pegasus unit.

Spectrum Technologies already utilises a wide array of pneumatic components from Festo, this includes pneumatic cylinders, valve manifolds and various types of sensors. Festo are therefore, the logical choice of brand for this module, as the supplier base is already well established.

Chapter 4: Concepts – Coil Stacking

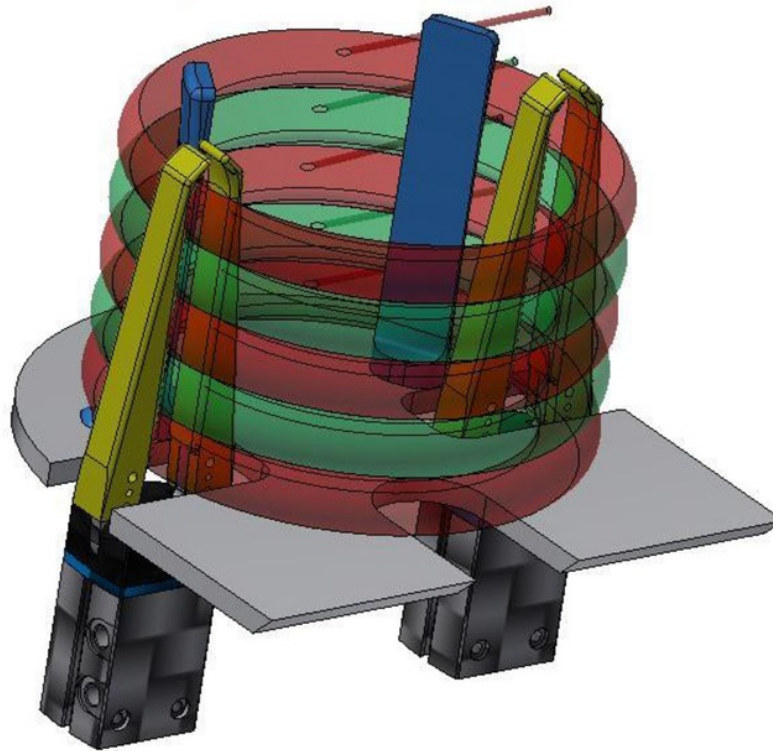


Figure 10 - Coil stacking platen - Concept 1 - Spectrum Technologies - 2018

This first concept for a coil stacking platen began with a 10mm aluminium plate mounted at a 30 degree angle from the horizontal, with notches to grant tying machine tool clearance. The principle aim in the first instance was to ascertain the optimal method for constraining coils. As can be seen above in figure 10, the coils are represented as they are shaped in the Pegasus hub, in actuality they would not be shaped as such.

Two Festo *DHWS angular grippers are represented here, each with a pair of jaws to clamp the coils. The angle of the aluminium plate was included to allow gravity to dictate the path of a dropped coil, should the robot tooling deposit one from above. The two guides (shown in blue) serve to 'catch' the coil as it falls.

This concept was dropped early on as it showed difficulties with constraining the coils. As the grippers open, their hold on the coils is released, and the coils are free to unravel and unwind. Also, the grippers were deemed too large for this application, and due to the length of the gripper jaws, reducing the gripper cylinder size would weaken the grip force.

Concerns were also raised with regard to the coil profile, further thought was needed to better approximate the dynamics of a coil once constrained and stacked among others.

*Festo products are identified with an arbitrary prefix, or collection of capital letters. The latter is not an acronym, as far as the author of this report is aware.

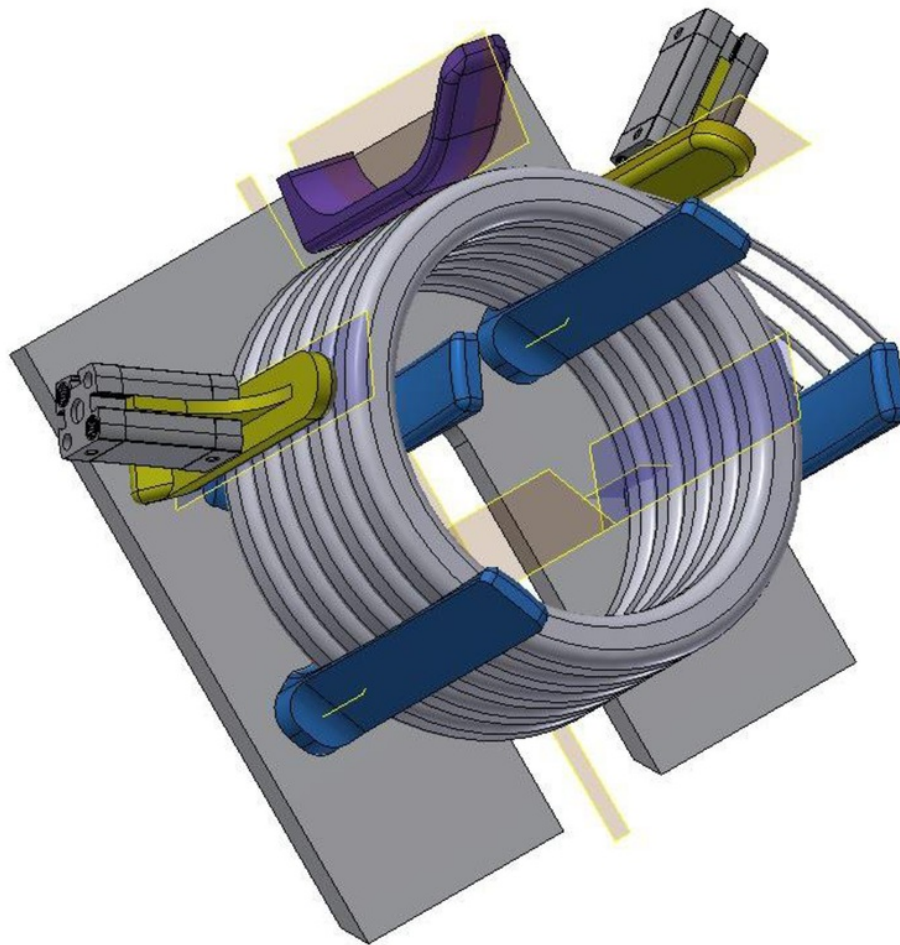


Figure 11 - Coil stacking platen - Concept 2 - Spectrum Technologies - 2018

The second concept retained the aluminium plate of the first, albeit with a single large notch instead of 3 smaller ones. The angular grippers are replaced with simple compact cylinders from Festo's ADN range, coupled with paddles to constrain the coils against the internal guides. The angle of the base plate has been increased from 30 degrees to 45, in an effort to better position the coils under gravity.

The coil shape was also refined, it now approximates a square cross section with rounded edges. The cross sectional area remains constant at 379mm².

This concept was also dropped for the same reasons as the first. It was largely a virtual thought process to visualise what was needed.

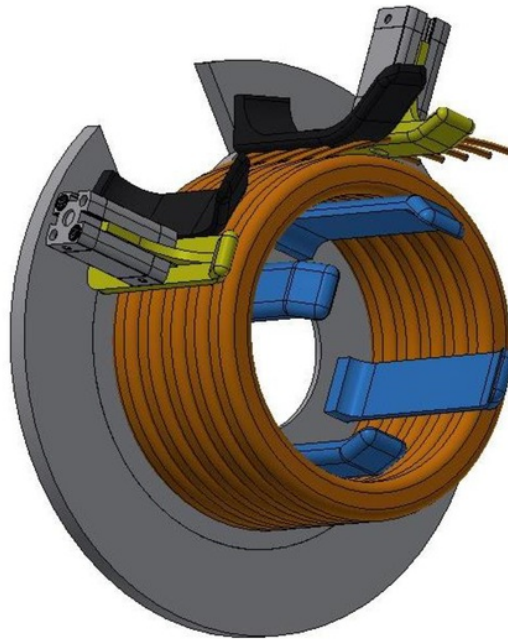


Figure 12 - Coil stacking platen - Concept 3 - Spectrum Technologies - 2018

The third concept for the coil stacking platen is similar to the second, but featured two round base plates, and more radial coil guides. The inner round base plate was intended to rotate axially, allowing a bundle to be tied in multiple positions. A method of indexing this inner plate was not explored at this stage.

The coil guides seen here, and in the previous concepts were intended to be 3D printed, using Spectrum Technologies' in-house 3D printer. It utilises Fused Deposition Modelling (FDM) technology, and is capable of producing ABS (Acrylonitrile Butadiene Styrene) parts with its dual modelling heads. One head extrudes molten ABS, the other a support thermoplastic material, which permits overhang geometries and other features, some of which are either extremely costly to produce by other means, or in some cases impossible. This support material is designed to be soluble in a specific alkaline solution at a specific temperature, permitting removal of the supports without the risk of damaging the part itself.

A tool such as an industrial 3D printer is an invaluable tool to have during the extended research and development stages of a project, as it can provide prototype parts quickly and accurately. The applications are widespread, as stated by Stratasys, a pioneering manufacturer of 3D printing machinery.

"From entrepreneurs to fortune 500 companies and large OEM's, companies have embraced advanced manufacturing and enterprise 3D printing to meet tough performance standards and satisfy firm requirements." – Stratasys Direct Manufacturing (2017)

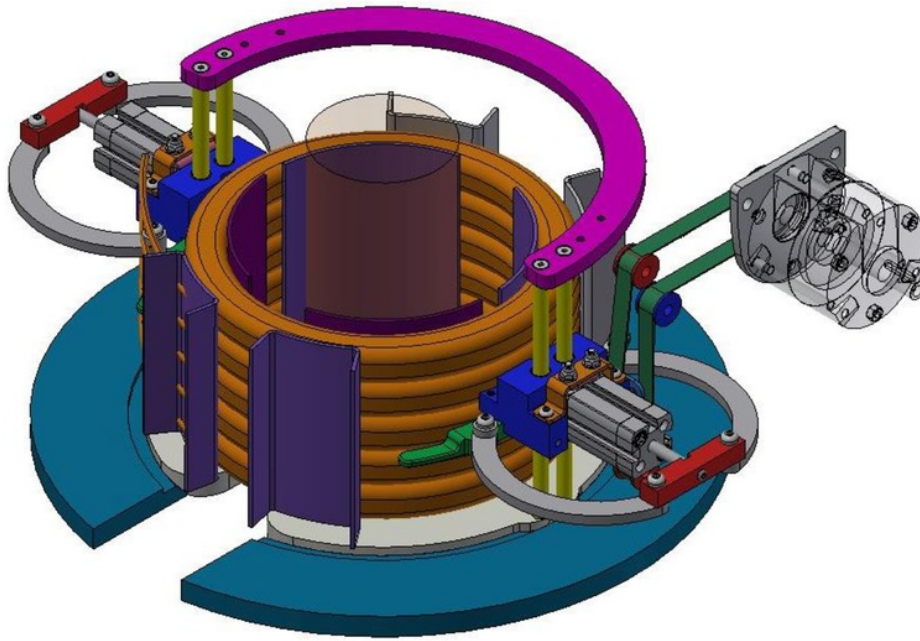


Figure 13 - Coil stacking platen - Concept 4 - Spectrum Technologies - 2018

The fourth concept expanded on a method of constraining the coils, in that it featured axial clamping, via the mechanism above. The green clamping fingers are retractable, and are actuated via the semi-circular arms, in turn actuated by a compact Festo ADN cylinder. The arms are semi-circular to allow clearance for the belt drive, this permits the mechanism to raise and lower, guided by the yellow guide rods.

The driving force behind the belt drive is provided by a Festo DRVS semi-rotary drive. This is a pneumatic device that functions via a vane connected to a shaft. This vane resides in a radial slot in the drive housing, which features ports at specific locations to enable pressurisation of the air gallery in front of, and behind the vane.

The semi-rotary drive features a protruding shaft with keyway slot, to allow pulleys or other components to be attached. In this case, a toothed pulley meshes with the toothed drive belt, which is in turn solidly affixed to the blue chassis block. The diameter of the toothed pulley then dictates the stroke of the mechanism. A method of belt tensioning is not shown in figure 13, but can be achieved through adjustable idler pulleys.

The platen itself carries forward the design seen in Concept 3, such that it is able to rotate axially, allowing bundles to be tied in multiple positions.

This concept required further improvement, and a method of rotating the platen is still required.

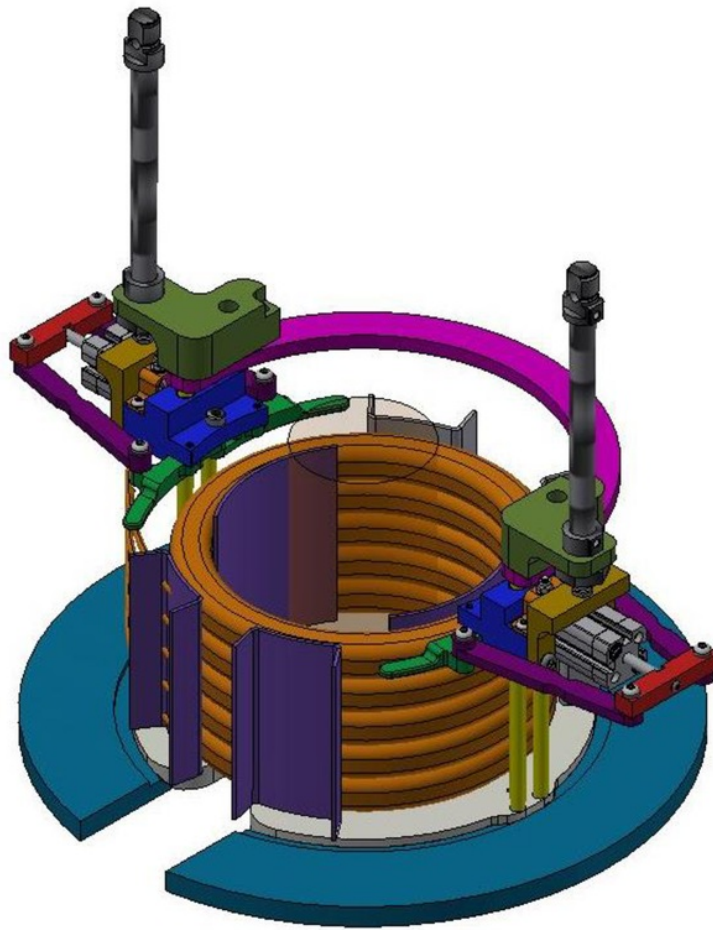


Figure 14 - Coil stacking platen - Concept 5 - Spectrum Technologies - 2018

The fifth concept is almost identical to the fourth, save for a simpler method of axial clamping. In this case, this is instead granted by mounting two Festo DSNU round cylinders, giving a clamping force in the same axis as that desired. This concept could be further improved by placing the cylinders as close to the yellow guide rods as possible, this will reduce the moment generated when the cylinders advance and reduce the probability that the mechanism will jam. The cylinders are as they are here, due to the need to position the robot tooling over the platen in order to deposit a coil.

To aid jam prevention, the tolerances between the blue chassis block and the yellow guide rods will need to be very close. An oilite bronze bush or polymer sleeve bearing would be ideal here, due to their low cost, longevity, and reasonable working tolerances.

The problem of rotating the coils relative to the tying machine remains, and at this point in the development, the need to have such a feature was called into question. While beneficial to the output of the module, it incurs a significant degree of complexity that is seemingly not possible both within the given timeframe, and within the restrictions posed by the choice of tying machine.

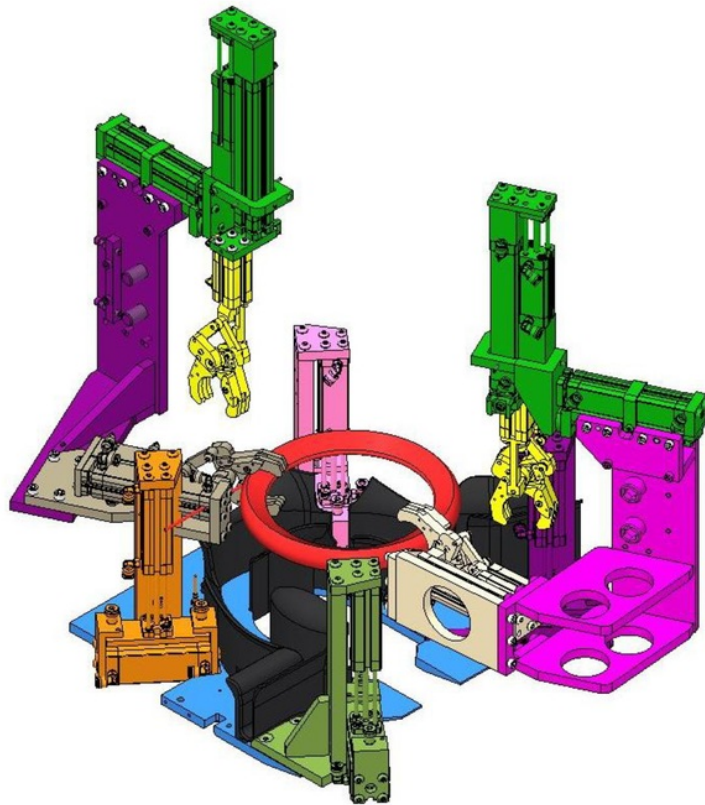


Figure 15 - Coil stacking platen - Concept 6 - Spectrum Technologies - 2018

This iteration of the coil stacking platen began on the basis that rotating the platen axially to perform multiple tying operations on the same stack was no longer feasible. This permitted a more direct approach to the overall design.

As with the previous concepts, it began with a 10mm thick aluminium plate, to serve as the base. This plate would always be kept parallel to the floor. The plate features a steep chamfer on its underside, this is to permit the tying machine to sit as close as possible to the coils. The performance of the XL-8 tying machine relies on this proximity.

This iteration is by far the most complex assembly generated so far, due to the sheer number of pneumatic actuators within it. Some can be operated in tandem however, such as the axial clamps, shown in figure 15 as orange, lime green, dark purple and light pink.

These clamps operate in pairs, with each assembly featuring two actuators, one for vertical movement, and the other, positionally governed by the latter, utilises its cylinder rod as the clamping implement.

The intent is for the orange and dark purple actuators to operate in tandem, and the same for the lime green and light pink actuators. If a coil is in place and clamped by both pairs, and a new coil is to be deposited by the robot tooling, one opposing pair will retract the lower, horizontal cylinder rods, and retract the vertical cylinders also, as below.

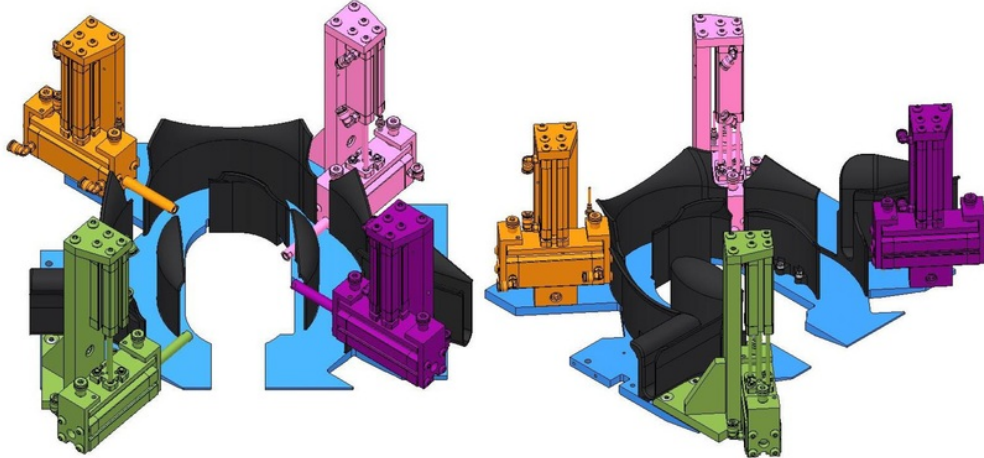


Figure 16 - Coil stacking platen - Concept 6 – Raised/retracted clamps - Spectrum Technologies - 2018

This opposing action results in the coils always being clamped, at any one time. Also, by virtue of the cylinder rods, they are free to retract even if a coil is clamped on top by the opposing clamps.

The black coil guides are 3D printed items, and feature flared top edges so as to guide the coils as they are transferred from the robot tooling, to the handover grippers. The guides also feature two troughs, one on either side of the platen, to serve as guides for the tail ends of the deposited coils. As the robot tooling orientation can be in one of two positions when depositing a coil, two troughs are present. For the final design, only one will be required as the robot tooling position will be fixed, relative to the platen and the surrounding apparatus.

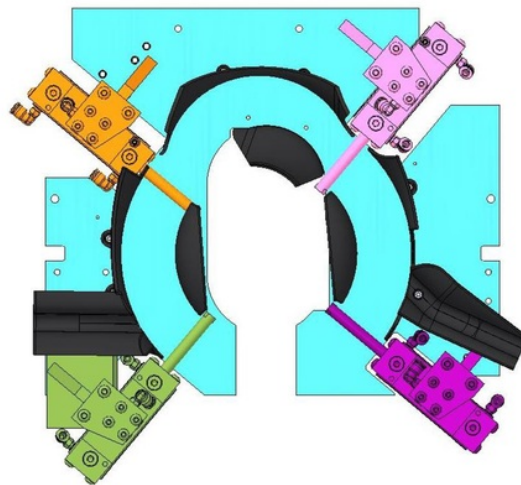


Figure 17 - Coil stacking platen - Concept 6 - Plan view of clamps and guides - Spectrum Technologies - 2018

The coil guides, as seen in the plan view of the coil stacking platen in Figure 17 are not arranged to form a perfect circle, they are not concentric due to the tying machine mechanism.

The clamp cylinders also feature a sprung bracket mounting, as seen below in figure 18, specifically in the orange assembly. The brackets are L shaped, and feature a shoulder bolt as a rod guide. This arrangement allows for further tuning of the clamping force by changing the springs.

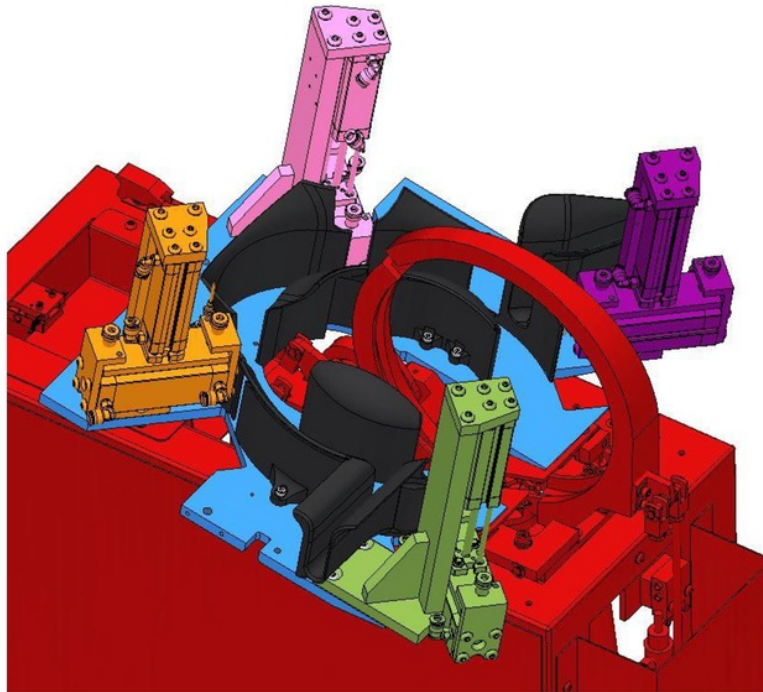


Figure 18 - Coil stacking platen & Tying machine - Concept 6 - Spectrum Technologies - 2018

This slight ellipticity distorts the coil profile somewhat but is deemed necessary and a much more desirable compromise, especially compared to the other available tying machines and the challenges that they represent for successful and reliable integration. The ratio of the ellipse form presented is equalised, the 'height' of the ellipse is increased, and the 'width' is proportionally decreased, so as not to disturb the lay and overall shape of the coils. Until such apparatus is constructed, further refinement would have minimal effect until the true dynamics of stacked coils can be ascertained.

The cylinders mounted vertically, are Festo ADNGF units, and feature guide rods to maintain orientation and resist bending moments. The size selected for the clamping operation are 12mm diameter pistons, which at 6 bar air pressure, generate 68N of force, theoretically.

This roughly translates to 6.93kg of force, this should serve to be more than adequate for clamping of stacked coils. If it proves to be too great, and the pushrod of the radially actuated cylinders leaves indentations on the wire insulation, the pressure and therefore force can be dialled back through use of a dedicated, in-line pressure regulator.

This will allow the force to be fine-tuned, helping to meet the stringent levels of quality expected by the end user.

The next issue to overcome is that of depositing a coil onto the platen. The robot end effector is large and cumbersome due to the number of different functions that it must perform, this limits its flexibility in terms of interaction with other assemblies.

As a result, any means of accepting a coil from the robot tooling must be capable of either depositing the coil onto the platen while maintaining a hold of the coil, or effect a second coil transfer to another assembly, which will then place the coil on the platen.

Given the available space, and the constraints in place by virtue of the robot tooling, the latter option is the simplest. The former option would require the gripping mechanism to pivot around the held coil, which would induce an unwanted twist. Also, the structure to support such a movement would be elaborate and costly.

A simple, straightforward transfer with no twisting motions is required, where the coil should ideally remain static until placed on the platen.

From this conclusion, two pairs of grippers are thus required, to operate a similar sequence as below;

- Robot tooling takes a handover position above the platen, sufficiently clear of all assemblies
- A suitable gripping mechanism extends radially inward to clamp the coil held in the robot tooling. Minimum of two primary gripping mechanisms required, phased at least 180 degrees apart to maintain coil shape and position
- Robot tooling releases the coil and retracts, ready to perform other tasks
- Secondary gripping mechanism extends radially inward, above the held coil
- Secondary gripping mechanism extends axially downward in a position as close as possible to the primary gripping mechanism jaws and moving sufficiently downward to seat the coil within the gripping jaws. Once extended, the jaws will close, leaving the coil held in 4 positions
- The primary gripping mechanisms release
- Secondary gripping mechanisms are now free to extend axially downward further, to hold the coil as close to the stacking platen as possible
- A pair of the stacking platen clamps retract radially and axially, then extend radially and axially, thus positioning the radial actuators piston rod over the coil
- The stacking platen clamps extend axially downward, clamping the coil against the platen/existing coils
- In the same instant, the secondary gripping mechanisms release, effecting a coil deposit.
- Repeat steps for next coil

This arrangement will incur a complex number of pneumatic actuators and sensors, the resultant motions will permit coil handling with greater care however. Twisting and stretching of the coil can cause damage both to the insulation and conductors within a coil of wire, both of which are unacceptable in the aerospace industry.

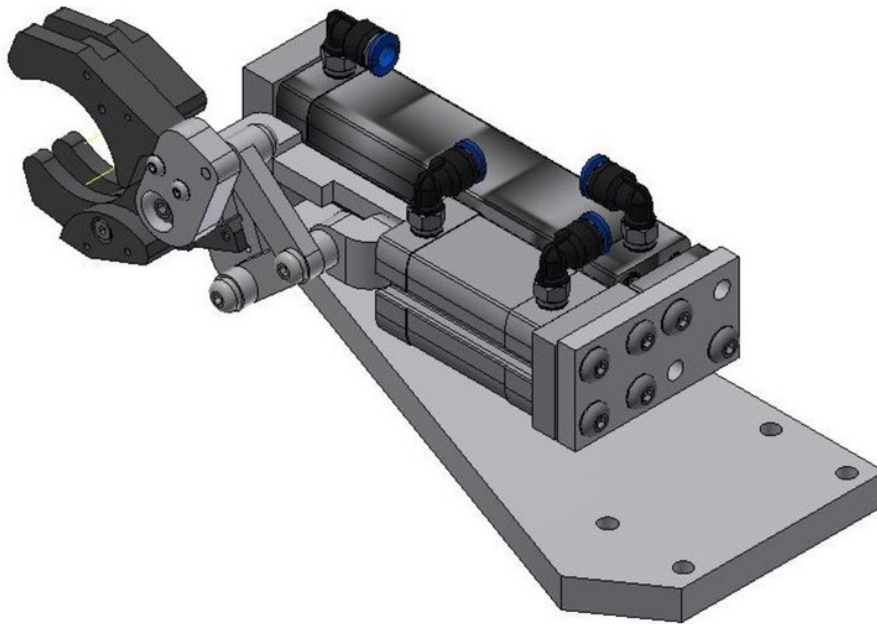


Figure 19 - Radial Clamping Mechanism – Concept 6 - Spectrum Technologies - 2018

As depicted above in figure 19, the radial clamping mechanism, of which there are two within concept 6, permits the controlled handover of a coil from the robot tooling. The short cylinder serves to drive the jaw mechanism, operated by an arrangement of levers. As the piston advances, the jaws close. Clamping force can be controlled via an inline pressure regulator.

The longer stroke piston serves to 'park' the mechanism away from the secondary (axial) clamping mechanisms, allowing the secondary mechanisms to operate and deposit a coil.

The jaws are shaped to mimic the human hand, in an anthropomorphic attempt to emulate the clamping action and holding ability. The jaw extents curve inward, as a thumb and forefinger would, with one major difference, the jaws are offset, allowing them to pass one another, closing the aperture down to a fraction of the original area.

The design of the jaws was influenced by the maximum coil cross sectional area, and by the physical constraints of interfacing with the robot tooling.

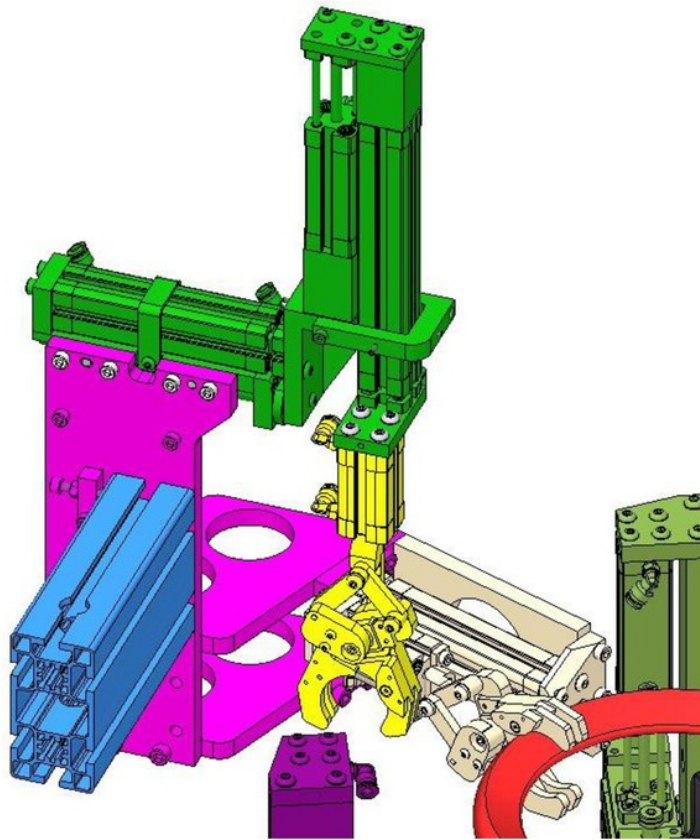


Figure 20 - Axial Clamping Mechanism - Concept 6 - Spectrum Technologies - 2018

The radial clamping mechanism can be seen above in figure 20, in beige, holding a coil in red. The axial clamping mechanism is seen in yellow and dark green and shares the same jaws and mechanism as the radial clamping mechanism. The dark green assembly governs the positioning of the axial clamp and has 3 stages of motion.

The horizontal cylinder advances, moving the entire assembly into position of the coil, held by the radial clamp. Due to the weight of this assembly, a supplemental guide rod is in place, directly underneath the cylinder.

The smaller of the two (dark green) vertical cylinders then retracts, lowering the clamp mechanism over the coil. The clamp cylinder actuates, constraining the coil. At this stage, the radial clamp mechanism can release and retract.

The larger vertical cylinder then advances downward, driving the coil towards the stacking platen. This cylinder features a relatively long stroke of 130mm. To aid rigidity, a brace is placed around the cylinder body, with tapped holes to mount nylon tipped clamping grub screws.

The vertical cylinders ultimately position the coil at such a height that the clamping cylinders (Figures 16, 17 & 18) can clamp the coil at the same instant that the axial clamping mechanism releases. The cycle will then repeat for the next coil.

Chapter 5: Final Concept

Concept 6 represents a complex and intricate method of achieving the goals for this module. Following a design review with the senior mechanical engineers, it was decided that development was progressing in the right direction. The coil stacking platen and its coil clamps would remain, however the radial and axial clamp mechanisms need to be simplified. Another means of effective coil handover must be conceptualised.

To achieve this simplification, an idea was explored that centred around using a simplified version of the robot end effector as a form of handover tooling. The logic behind this idea is that the robot end effector is designed to accept a coil handover from the Pegasus hub, it should also be equally capable (bar some minor modifications and omissions) of accepting a coil from a similar assembly.

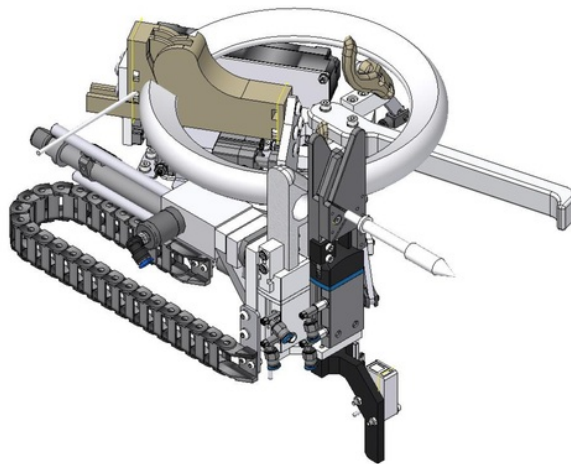


Figure 21 - Robot End Effector Tooling - Spectrum Technologies - 2018

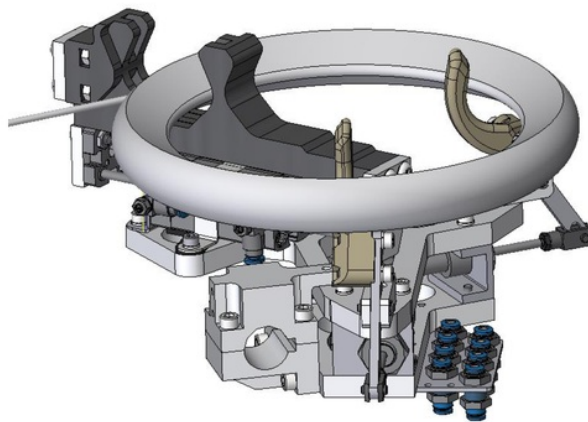


Figure 22 - Simplified Handover Tooling - Spectrum Technologies -2018

A comparison between the two assemblies shows in figures 21 & 22, that the same method of coil retention is utilised, comprising of two fingers and an apex clamp, equally spaced at 120 degrees from each other to minimise coil deformation.

As seen in figure 22, the simplified handover tooling is essentially a stripped down version of the robot end effector tooling. The key elements are retained, those being the two curved coil retaining fingers, and the coil apex clamp. The latter has been refined to avoid a crash upon undertaking a coil handover.

A critical aspect of a coil handover using these two very similar assemblies is one of wire tail end control. The robot end effector clamps the wire coil at its apex, or where the nose and tail of the wire cross. The handover tooling must also clamp as close as possible to this point, preferably on the wire tail end side, as this is always greater in length than the wire nose end.

This is due to the way the wire is coiled within the Pegasus machine, it starts the coil from the nose wire position, which is always at a fixed point in space. As the coil is wound, the nose is continually clamped in place, and so cannot increase nor decrease in length, and remains in a constant position relative to the coil apex.

Due to the clamp geometry of the robot tooling, the handover tooling must be offset by 25 degrees in order to avoid interference.

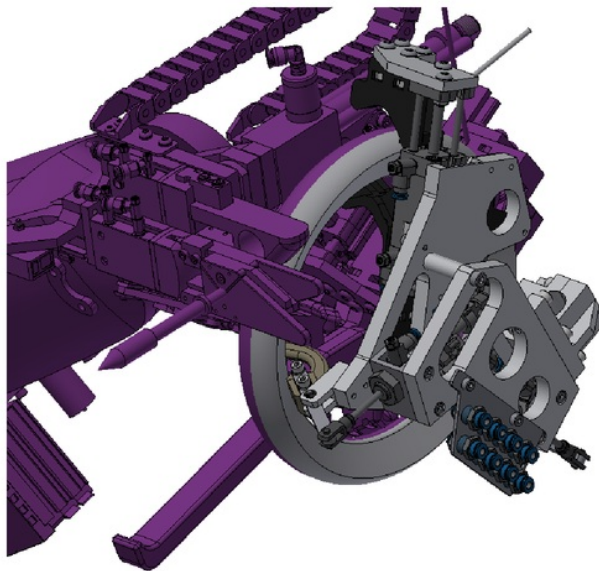


Figure 23 - Handover & Robot Tooling Interface - Spectrum Technologies - 2018

As above in figure 23, the handover and robot (purple) tooling interface in such a way so as not to clash. It is to be noted that pneumatic lines and sensor cables are not represented but have been considered during the design stage. The bundle collection peg can also be seen here, extending to the bottom left of the image. This peg will be used to remove the tied bundle from the stacking platen, and transport it to the collection carousel.

Some parts are common to both assemblies, in this case the actuators for both the apex clamps and all 4 of the retaining fingers. The decision to re-use existing assemblies brings benefits other than existing drawings and in-system parts, the major benefit is that the assemblies are tried and tested, and are therefore a more reliable option when compared to a new concept for the given application.

From this point, the significant challenge of utilising this handover tooling to present a coil to the stacking platen clamps was the next task.

The thought process for how to manipulate the handover tooling in order to deposit a coil began with identifying the required end position. As the starting position is known, as per figure 23, with the coil facing outward, away from the module. Therefore, the end position will be behind and below the initial position, and a rotation of 90 degrees.

At this stage, it was realised that the assemblies to manipulate the handover tooling would have to move aside to permit the robot tooling clearance to pick up a bundle, once the tying operation was complete. The simplest method would be to mount the assemblies onto a movable arm, that would pivot around a point outside of the module, such that the assemblies could safely be stowed in a position allowing the robot tooling clear access without a need for complex movements.

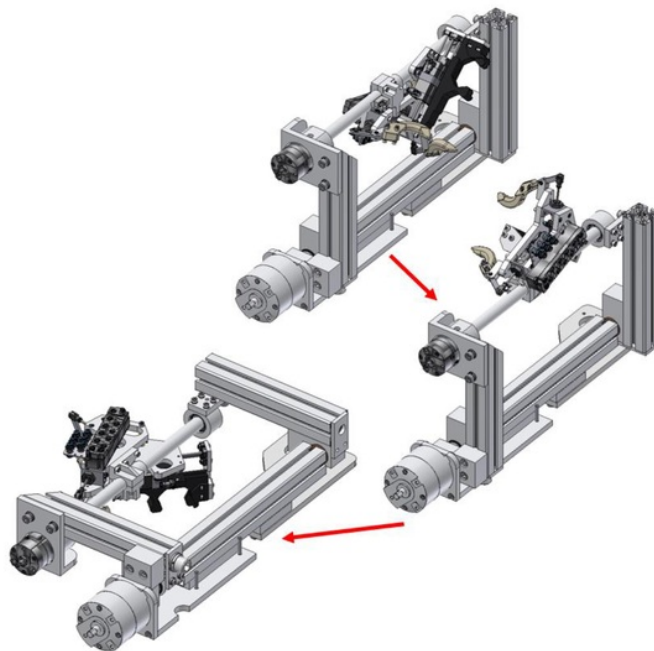


Figure 24 - Handover Tooling & Swing Arm - Final Concept - Spectrum Technologies - 2018

The above assembly shown in figure 24 was generated to perform the movement required to deposit a coil. The design began with an aluminium shaft, supported at one end by a deep groove ball bearing and retained with an internal circlip. This shaft represents the (primary) axis of rotation for the handover tooling, and is driven by a Festo DRVS semi-rotary vane actuator.

It was discovered that the distance for the parallel (secondary) axis of rotation (driven by the larger Festo DRVS unit) required to correctly position the handover tooling over the stacking platen, and in the raised position, remain in the robot's field of reach, dictated that the primary axis of rotation could not be ninety degrees due to the volume of space occupied by the handover tooling when a coil is held. If the handover tooling were to rotate through the shortest arc of 90 degrees, it would clash with the supporting framework. Therefore, the handover tooling must rotate through the opposite direction, through 180 degrees.

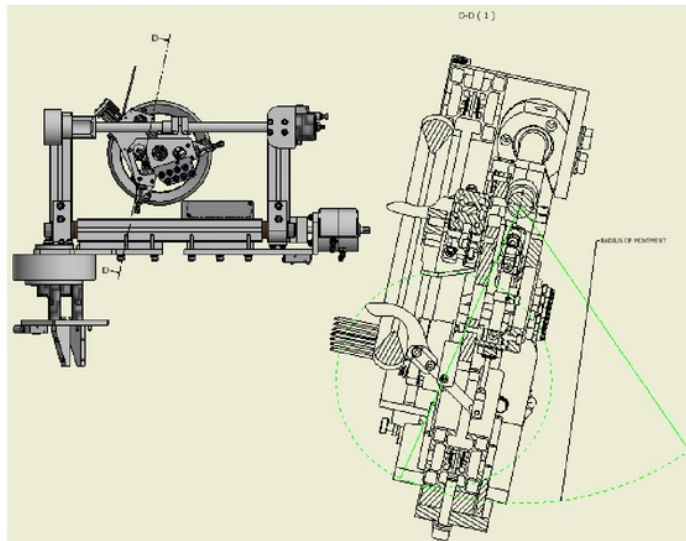


Figure 25 - Handover Tooling Primary Axis of Rotation - Final Concept - Spectrum Technologies - 2018

The above figure illustrates the clearance issue. From section D-D, the shortest arc would be through 90 degrees, counter clockwise. This is not possible, and so the handover tooling must rotate through 180 degrees to reach the horizontal position with the coil facing downward. This is also dependant on the secondary axis of rotation, provided by a second DRVS actuator which brings the handover tooling into the proximity of the stacking platen.

In order to specify a suitably sized Festo DRVS Semi-Rotary Vane actuator, the minimum required torque to rotate must be calculated. This was done through using CAD software to approximate the centre of gravity of the handover tooling, and its relative position to the axis of rotation.

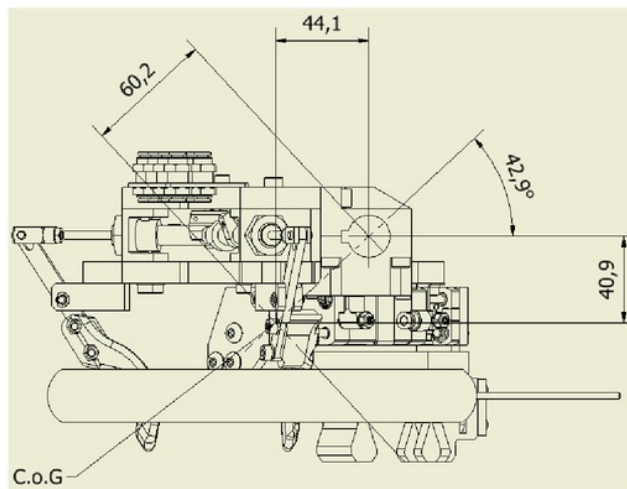


Figure 26 - Handover Tooling - Torque Calculations - Spectrum Technologies – 2018

Approximated final mass = 2.8kg

Approximated final weight = $2.8 \times 9.81 = 27.468\text{N}$

Required torque = $27.468 \times 0.0602\text{m} = 1.654\text{Nm}$

Based on the calculations in figure 26, an actuator with a torque rating of 2Nm or greater at 6 Bar must be specified.

Semi-rotary drives DRVS

Technical data

FESTO

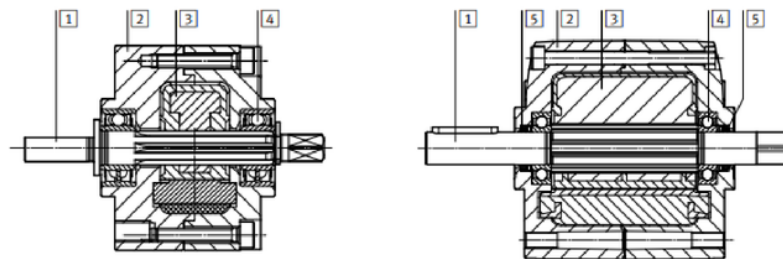
Weight [g]							
Size	6	8	12	16	25	32	40
Swivel angle of 90°	38	68	154	272	502	928	1530
Swivel angle of 180°	38	68	152	270	494	912	1500
Swivel angle of 270°	–	–	150	268	486	896	1470

Materials

Sectional view

DRVS-6/8

DRVS-12 ... 40



Size	6	8	12	16	25	32	40			
1 Drive shaft	High-alloy stainless steel			Nickel-plated steel						
2 Housing	Anodised wrought aluminium alloy		Painted die-cast aluminium							
3 Rotary vane	Reinforced PET									
4 Ball bearing	Rolled steel									
5 Shaft seal	-		PU		NBR					
- Screws	Galvanised steel									
- Seals	TPE-U(PU)									
Note on materials	RoHS-compliant									

Forces and torques							
Size	6	8	12	16	25	32	40
Theoretical torque							
At 6 bar [Nm]	0.15	0.35	1	2	5	10	20
Per bar [Nm]	0.025	0.058	0.166	0.33	0.83	1.66	3.33

Figure 27 - Festo DRVS Semi Rotary Drive Datasheet - Festo – 2018

According to the datasheet, the size 16 DRVS actuator is an ideal choice, capable of generating 2 Nm at 6 Bar. Extrapolating from the approximate values for maximum theoretical torque in figure 26, the margin for error in terms of weight is as follows.

$$2\text{Nm} \div 0.0602\text{m} = 33.22\text{N}$$

$$33.22\text{N} \div 9.81 = 3.387\text{kg}$$

Therefore the theoretical maximum weight (provided that the centre of gravity remains in the same position) that the actuator can drive is 17.33% greater than the approximated weight of 2.8kg.

The same calculation also applies to the secondary axis of rotation, but in this instance the required torque will be much higher.

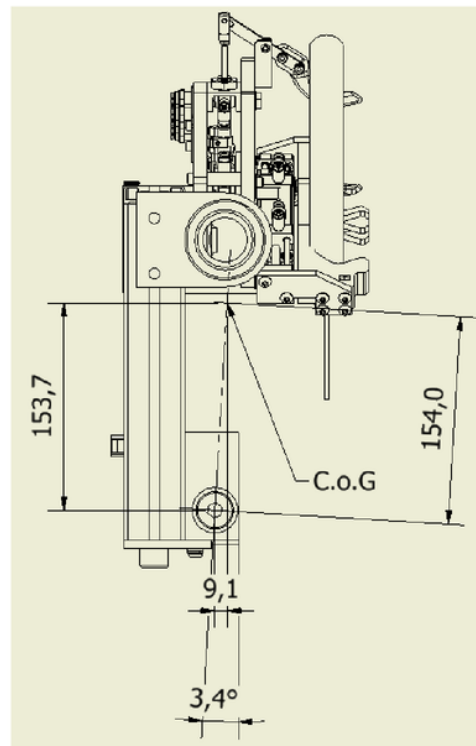


Figure 28 – Secondary Axis of Rotation – Handover Tooling – Spectrum Technologies – 2018

Approximated final mass = 5.57kg

Approximated final weight = $5.57 \times 9.81 = 54.642\text{N}$

Required torque = $54.642 \times 0.154\text{m} = 8.415\text{Nm}$

Again referring to figure 27, in this case the size 32 cylinder is the most suitable, with a theoretical torque output of 10Nm at 6 Bar.

The margin for error in the weight approximation is as follows;

$$10 \div 0.154 = 64.935\text{N}$$

$$64.935\text{N} \div 9.81 = 6.62\text{kg}$$

Therefore, the theoretical maximum weight for this assembly provided that the centre of gravity position remains constant, is 15.86% greater than the approximated weight.

Using the datasheet in figure 27 to obtain the operating forces and torques for these cylinders also highlighted the fact that Festo also offer dedicated mounting hardware, which provides the benefit of saving design time, cost, and reduces the overall drawing control overhead.

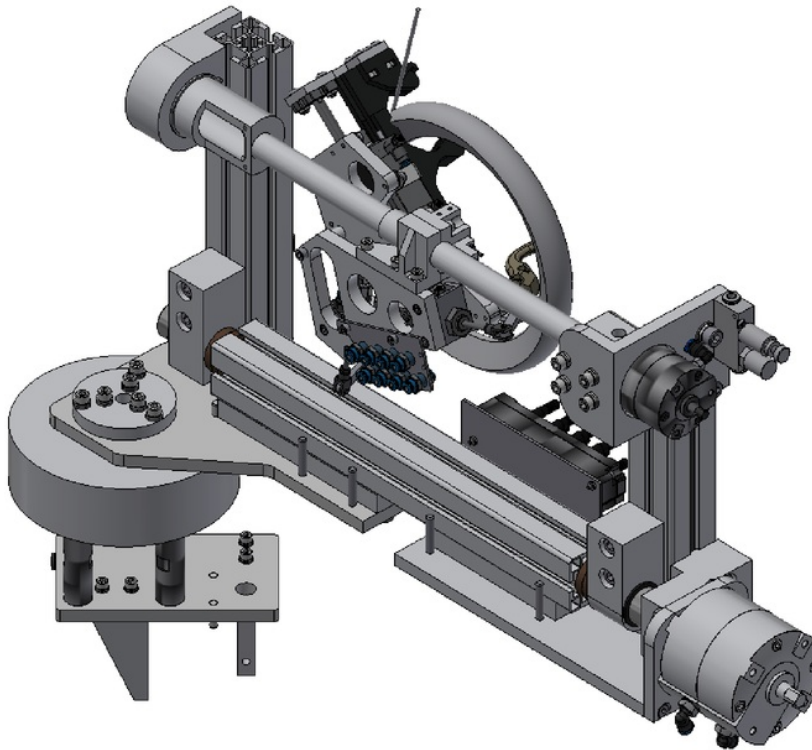


Figure 29 - Handover Tooling - Final Concept - Spectrum Technologies - 2018

Elements of the handover tooling were designed with adjustability in mind. This module is the first of its kind and is a relatively unknown and unexplored area of wire / coil handling.

To grant flexibility with regard to setup, trouble shooting, and fine tuning, the module features lengths of slotted aluminium extrusion, which permits components to be moved along its length, and bolted in place through use of proprietary T-nuts. Spectrum Technologies utilises the Maytec extrusion system to great effect in this regard.

Also, in efforts to minimise the weight of components and of the overall structure, lightening holes have been added to the dynamic elements of the assembly. The Maytec aluminium extrusion also plays a key role here, as it is a markedly cheaper alternative for bespoke machined parts, which incur higher costs for machining operations when large volumes of material are required to be removed in order to shed weight from a component.

It was noted early on that the issue of pneumatic line and data cable routing, as well as the sheer number of the two, could potentially hinder the operational effectiveness of the assembly. To combat this, specific paths and strain relief mounting points have been designed into the components. For example, the handover tooling features numerous tapped holes for P-clips and cable tie bases, and the primary axis shaft features a hollowed out portion at one end to permit pneumatic lines clearance from the handover tooling, as they are now able to rotate via a relief loop in open space, as opposed to in close proximity to the handover tooling.

Various components also feature mounting facilities for pressure and flow regulators, should they be required.

Also seen in figure 29 is the main pivot point. This arrangement houses a third Festo DRVS cylinder, and exists to enable the stowing of the entire assembly aside, allowing the robot tooling to retrieve a tied bundle. This assembly represented a significant challenge, both to overcome the significant moment as a result of the large cantilever arrangement, and to engineer a way to house the pneumatic cylinder such that it can operate without experiencing any adverse loading.

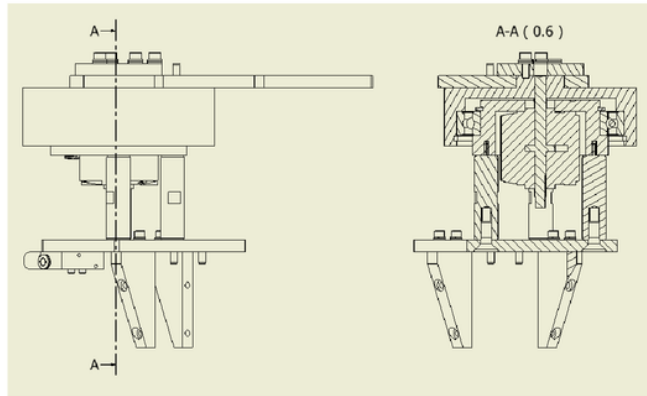


Figure 30 – Pivot Point – Final Concept – Spectrum Technologies - 2018

Providing access to its inlet and exhaust ports was also a concern, as an 8mm spanner is required to tighten the standard Festo M5 to 6mm elbow fittings.

Another concern was to allow room to fit the proprietary position sensing unit for the DRVS cylinder, offered by Festo. This unit locates on the rear face of an actuator, and affixes both to the chassis and to the stub shaft that protrudes through the rear face. The sensors that integrate into this assembly are only available in the straight connector type, and therefore can only be fitted parallel to the axis of cylinder rotation. This meant that the underside of the DRVS cylinder was required to have a certain amount of clearance. The consideration of maintenance was addressed at this stage, as sufficient clearance is not only required for the sensor body and data cables, but for the hand of a technician checking connection integrity.

To address this, the mounting chassis for the cylinder was designed to fit to 3 configured pillars from Misumi, which feature a female and male thread, with wrench flats. These are made from 304 grade stainless steel, and are cheaper from Misumi than to have them custom machined. These pillars are equally-spaced across a 270 degree arc, leaving an exposed area for access to the pneumatic connections and sensors for the lower DRVS cylinder.

The cylinder mount also serves as the inner bearing surface, to suit a 6920 series bearing (OD 140mm, ID 100mm, Width 20mm – Misumi). A large 100mm external circlip is used to retain the bearing. The outer housing is the driven element, and so has tapped holes and locating boss to mate to other parts. It also features an internal counterbore for the bearing, and is designed to accept a 140mm internal circlip, to retain the bearing.

Both housings are manufactured from 6082-T6 aluminium, selected for its strength, availability and machinability. To properly ensure that the majority of load is transferred to the bearing, and not to the actuator shaft, tight tolerance fits are used on the locating boss in the mounting plate, a H7 – g6 clearance fit, this gives a clearance of between 9 and 50 microns (Simply Bearings, 2019). The top plate is also used to clamp the outer cylinder housing and the mounting plate together, giving the assembly increased rigidity.

The next task centred around producing a supporting framework for the module, which began as seen below, utilising the Maytec modular aluminium extrusion system.

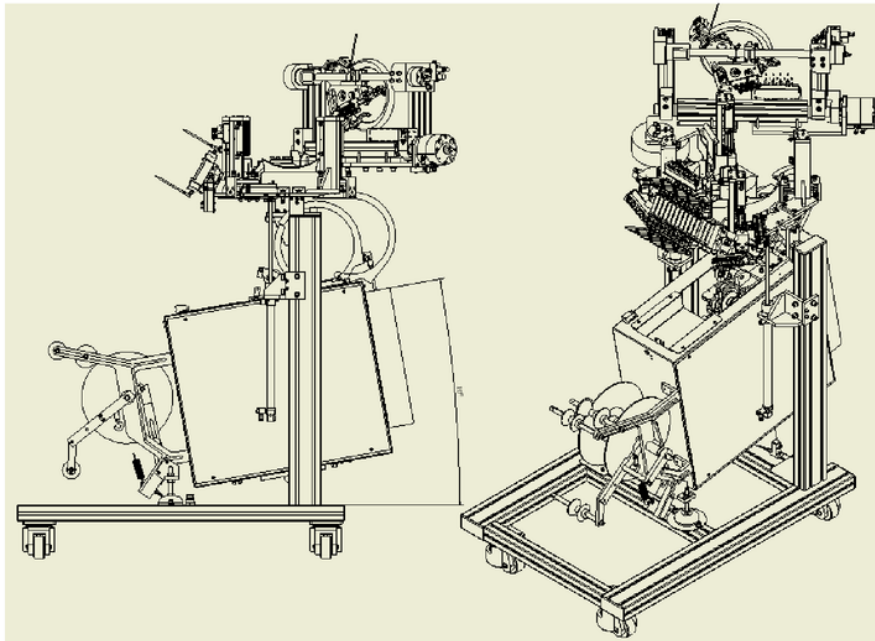


Figure 31 - Base Frame - Final Concept - Spectrum Technologies - 2018

The frame features cross members to support the XL-8 tying machine, with a pivot mount in-between the vertical frame members. The rearward cross member supports a jacking foot, that is used to achieve the optimal positioning angle of 10 degrees from the horizontal.

This angle is required to allow the stacking platen, and therefore the coils of wire, to be situated as close as possible to the tying mechanism.

The vertical frame members serve two purposes. The first, is to permit mounting of supporting bracketry for the vertical pneumatic cylinders. These position the stacking platen, and are assisted by ball bearing slide units that run up each vertical member, on the inside face. The vertical pneumatic cylinders are specified to have adjustable end range cushioning, to lessen the impact of reaching the end of their stroke, which is 250mm.

The piston diameter of the cylinders is specified at 20mm, which theoretically grants 189N of force at 6 Bar. 2 cylinders together should net 378N of force, which equates to approximately 38.5Kgf.

This is an over-specification, as the diameter of the piston rod grants additional rigidity and stability. The mass of the stacking platen is approximately 13kg, without any coils deposited. The cylinders are capable of lifting more than double this amount, this accounts for the relative unknown with regard to maximum coil weight. Relative unknown is an applicable term as the outer diameter of the wire does not account for the conductor thickness, and so wires of the same diameter can vary greatly in weight per metre.

Further considerations for the weight of the stacking platen is the addition of the Festo pneumatic valve manifold, which itself weighs 2.7kg. It features 14 valve positions, of which 3 are blank for redundancy/future developments. There is one valve per cylinder, however in this application, a particular valve can drive multiple cylinders, for example the clamp cylinders on the stacking platen operate in opposing pairs.

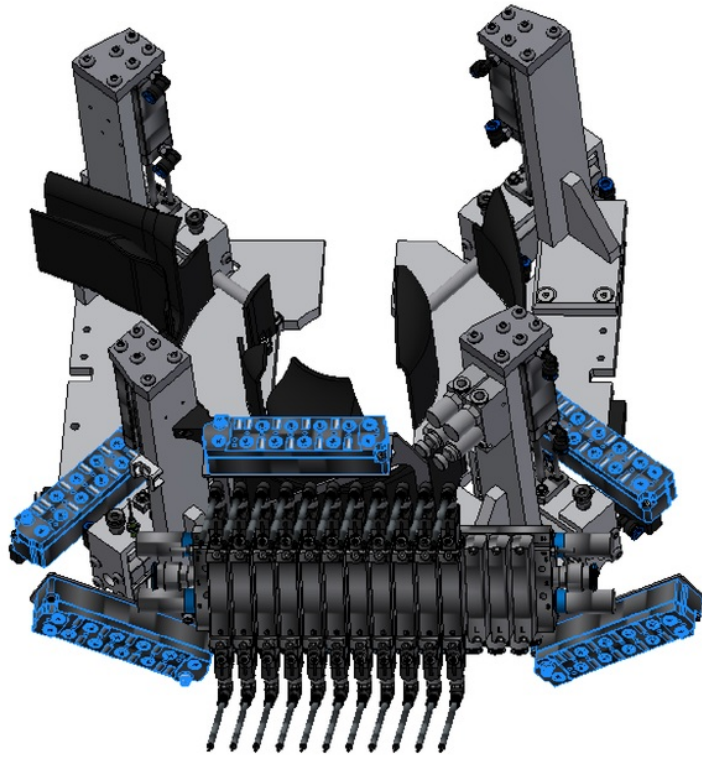


Figure 32 - Final Concept - Stacking Platen IO Blocks - Spectrum Technologies - 2018

Each valve has two outputs, which are controlled via an external PLC. For efficient and compact connections outside of the module, Input Output (IO) blocks are used, highlighted in blue in figure 32. These allow multiple connections to be amalgamated into one signal cable. There are 11 active valves, and therefore 22 outputs. Each IO block features 8 ports, therefore 3 IO blocks are required, for a total output count of 24.

The remaining two IO blocks are there for the reed switches, used for position sensing and potentially fault monitoring, however this is ultimately reliant on the software programme.

The mounting of these IO blocks was carried out with consideration to the available sensor cable and connecting cable lengths, and the required routing to avoid pinching and chafing with the moving assemblies. To this effect, extra tapped holes in the vertical clamping cylinder mounts provide a means of attaching cable tie bases for cable and pipe control.

The final concept required adequate guarding, to permit safe operation within the robot cell, and to not impede the functionality of the module.

In this case the guarding is required to have a minimum height of 1644mm, which then matches the height of the adjacent modules within the robot cell. The guarding must also provide access to the machine, for maintenance, servicing, and tying material replenishment.

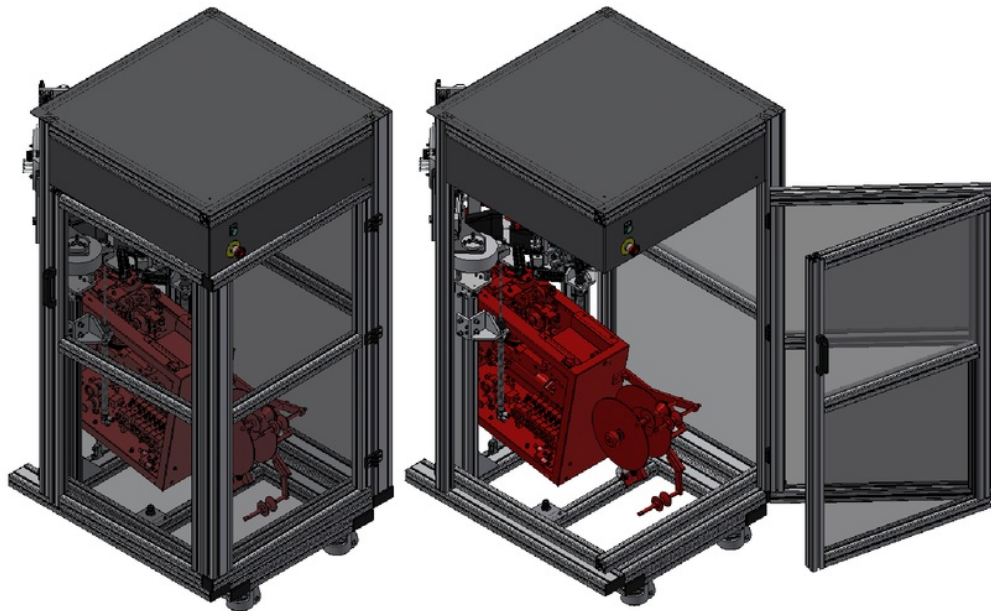


Figure 33 - Final Concept - Module Guarding & Door - Spectrum Technologies - 2018

Figure 33 depicts the resultant design, which achieves both the height and width requirements of the module, 1644mm & <1m respectively. The precise width is 820mm. The door is of a double hinge design, to allow maximum access to the internal components. To conform with the guarding standard previously mentioned, an interlock system must be implemented, this will be addressed in the future.

The frame work is comprised of Maytec aluminium extrusion, chosen for its flexibility, and ultimate modularity, as the surrounding equipment within the robot cell is also constructed as such. This allows simple module connection and positioning. The roof and fascia panel are manufactured from powder coated 2mm thick aluminium, in keeping with the Spectrum Technologies aesthetic. The fascia panel also serves as a mounting location for a status light and emergency stop button.

The frame also features stops in the form of aluminium extrusion, along the bottom edge of the door, this prevents the door from striking the equipment within. There is also a bulkhead plate situated underneath the tying machine to connect air services.

Lastly, the handover tooling will pivot to the side, granting clearance for the robot tooling to close in and pick up a tied bundle. A best guess approximation of the coil form once tied was generated, utilising close grouped circles which represent the wires. These preserve the voids present in an actual coil, as circles in close proximity leave gaps between them. Thus a bundle model was generated, with a total cross sectional area of its wires equal to that of the stated maximum, 1895mm².

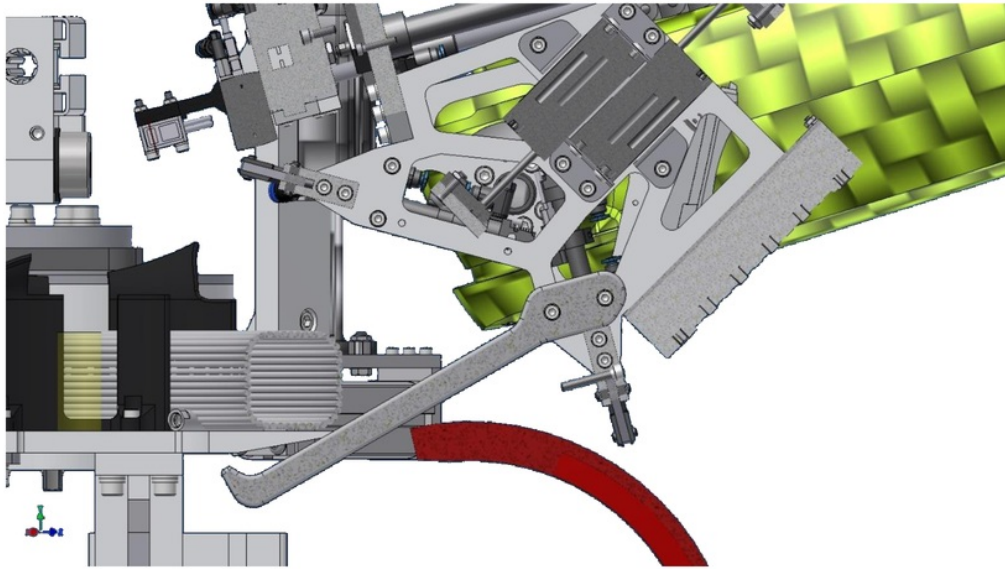


Figure 34 - Final Concept - Robot Tooling Bundle Retrieval - Spectrum Technologies – 2018

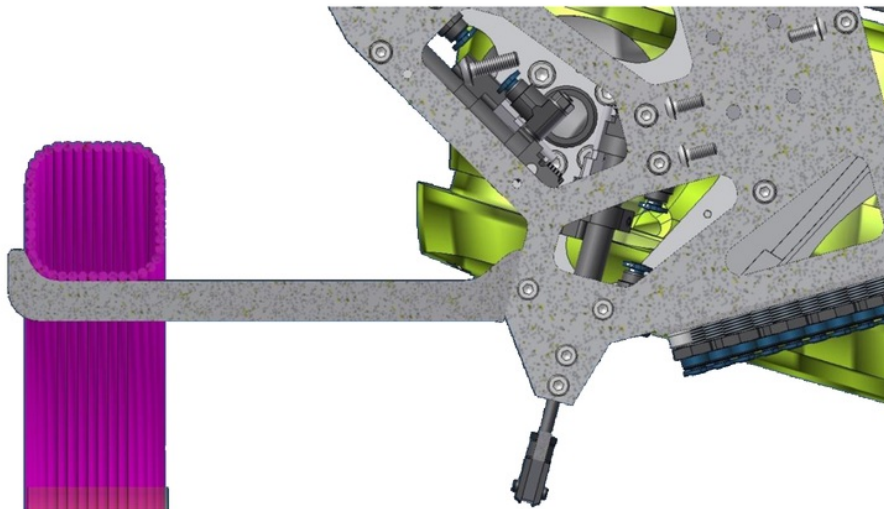


Figure 35 - Robot Tooling Bundle Peg - Spectrum Technologies – 2018

Robot tooling acceleration will have to be tuned to acceptable levels, so as not to dislodge the bundle upon retrieval and deposit onto the collection carousel.

Chapter 6: Theoretical Functional Analysis

The module as a whole, while having not been physically constructed, has been undertaken with an element of risk, the risk being that the intended functionality is considerably complex due to the variables in the form of wire types. The dynamics of each wire type differ, as previously mentioned, in shape, diameter, weight, inherent memory, insulation jacket frictional coefficients (pertaining to how well they are gripped/clamped) and ultimately length.

It is almost certain that the design of the wire guides and likely the clamping mechanisms will change as development of the module continues in the near future.

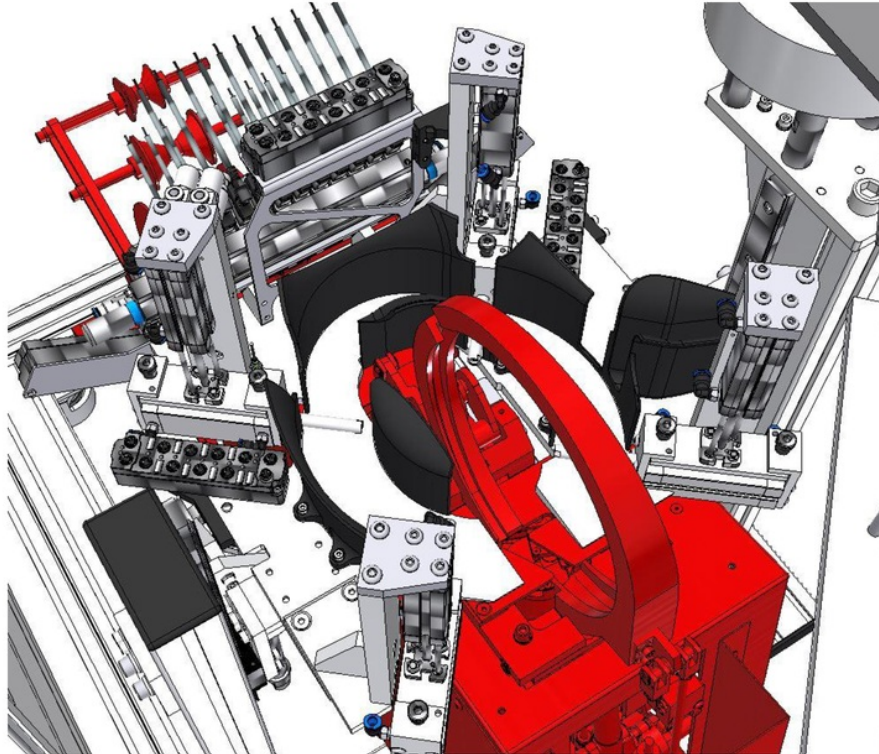


Figure 36 -Final Concept - Stacking Platen and Tying Machine - Spectrum Technologies – 2018

The tying machine also represents a second unknown, as it has not been designed with integration within its scope. While the XL-8 Air Ring Tyer is objectively the most suitable, it may not perform as intended due to the addition of the stacking platen around its operational area. The efficacy of the tie is dependant on the proximity of the item to be tied to the tying machine, the thickness of the stacking platen introduces an offset. The tying machine has a variable tying tension setting, this will be key to achieving a suitable tying tension, such that the bundle does not unravel.

With regard to the handover tooling, the main constraint was that the robot tooling was never designed to accept a coil from anything other than the main Pegasus hub. As such, the coil handover may prove problematic during the testing phase, despite the indications in the CAD model of clearances. Moreover, changing elements of the robot tooling was not in the scope of the module at the time of design.

Chapter 7: Conclusions and Recommendations for Further Development

This module is the culmination of a design study that is not comprehensive. The mechanical conceptualisation and design are a result of efforts from a single person. The overall design process has received input from other engineers, but the overall result is a module that is not a result of collaboration and compound thinking. In a typical industrial project, a design specification is usually generated, and a team of persons assigned to critically appraise and refine it, until a unanimous, finite specification is decided upon. Each decision, idea and change should be the result of continuous checking and rationalisation, to produce an efficient and relevant design under the project scope.

Due to time and resource constraints, this project was constrained to a small time period that in respect to the complexity of the desired end result, was not conducive to such an undertaking. The task at hand centres around the practice of wire coil handling, and the current Spectrum Technologies team has minimal experience in designing such equipment, much less implementing a module into an automated robot cell. To that end, this venture represents a risk on behalf of the business, such that the end result has a high probability of failure. The given timescale limited the critical analysis and refinement practices and this, coupled with the lack of finite design specification did not produce a clear direction, and instead progressed under an 'Open specification'.

This approach to such a complex task has produced a radical and costly assembly, the conceptualisation of which has relied heavily on speculation, conjecture and rough estimates.

Given the minimal experience in the area of wire coil handling of Spectrum Technologies staff, this module had to be designed from the ground up, utilising unknown and unproven techniques to achieve various performance goals. While such practices may be prevalent to encourage lateral thinking, without clear direction and thorough peer checking, ideas and concepts can quickly become overly complex. The concepts generated for this project convey the thought process and approaches used, as well as the progression as ideas were logically eliminated. Where ideas displayed potential and a possible way forward, they were pursued accordingly. The assemblies generated for this project may perform as intended in some areas, but may suffer in others, specifically with regard to the variables presented by the wire coils, and the dynamics thereof. Until such a unit is built and experimented with, it is difficult to speculate as to how the various aspects of the machine will perform.

Recommendations for further development would be to define an operational pneumatic sequence, applying a naming convention to the various cylinders and their respective valves, as well as all the sensors intended for use. This could be used to aid development of software for the module, and to generate a pneumatic diagram for fault finding and diagnosis purposes.

Depending on the initial testing and experiments, it may be required to alter the components of the tying machine, in order to improve or change certain geometry or operational characteristics.

This should not be overlooked as part of the development process. Furthermore, the robot tooling should also be included, to better interface with the handover tooling while aiming to retain its core functionality about other modules. This is a critical aspect of the module functionality and could potentially avoid handling errors. Also, the sheer number of pneumatic lines and sensor cables that are subject to dynamic assembly elements realistically requires a form of strain relief, which has not currently been implemented.

The design is recommended to be systematically broken down and ratified, to better understand how it will perform and to identify any errors on the engineering drawings. Such errors can greatly hinder a prototype build, and lengthen timelines, peer checking of drawings will largely eliminate such issues. Given enough time and resources, a redesign of the module may prove to be a more rational business decision.

In principle, this module is a novel concept for automated wire-coil handling. It will yield significant benefits to a potential customer in the aerospace industry by helping to reduce the human error factors that are part of every industry if it proves itself to be functional.

Critically, the individual elements of the coil handling system are somewhat over engineered to account for the relative unknowns of bundling and coil manipulation. A significant BoM cost reduction could be achieved through identifying parts that can be either omitted entirely, or simplified.

The final recommendation for the module is in the form of condition and status monitoring, currently the assemblies are devoid of sensors outside of the pneumatic actuators. The operational stability of the system could greatly benefit from additional sensing for coil status, coil position checking, and overall status monitoring. Cameras to provide viewpoints to the operators via a remote network connection or local to the Pegasus machine would allow them to visualise the machine status or check if the tying material is near depletion.

Alternatively, a dedicated sensor could be used to detect if the tying material is low. Currently, the system requires operator interaction to physically replenish tying material. It may be beneficial for an automatic reloading system to be implemented, however this would represent significant further complexity and cost, for minimal gain.

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